

AN ULTRASONIC PULSER/RECEIVER SYSTEM WITH EXTENDED DYNAMIC RANGE AND LOW DISTORTION

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INTRODUCTION

The increasing sophistication of quantitative ultrasonic techniques and signal processing requires signal electronics systems having performance characteristics which are significantly better than those of conventional designs. Better performance, in terms of extended signal dynamic range, stability, bandwidth, and signal distortion, is becoming essential for many applications in the laboratory and in the field; further, software control of large automated systems often requires specialized circuit configurations, which are not available.

This paper addresses the design of an ultrasonic signal system which has proven very useful as the major signal-conditioning component in obtaining improved performance in large, automated ultrasonic systems. Extended dynamic range comes from improvements in the signal/noise ratio (SNR). Both terms in the ratio are addressed, increased sensitivity through pulser design, and noise primarily in receiver design and careful attention to circuit details. The system is entirely modular and includes provisions for software-driven gain control and random multiplexing of many channels.

The key, and most difficult, elements in the system are the pulser and amplifier. The major part of the discussion will be on these elements and the rationale for their design, rather than on circuit details. Use of these elements in large automated systems [1] and in laboratory investigations [2] will also be discussed.

PULSER

The ideal excitation for pulsed piezoelectric transducers in most applications is a mathematical delta function. In practice, it is necessary to reach full available voltage across the transducer in the first quarter cycle of the transducer's mechanical resonance in order to obtain the most effective excitation and, thus, highest sensitivity. The biggest part of the problem is obtaining the full voltage quickly.

The piezoelectric element is equivalent electrically to a leaky capacitor with a small parasitic inductance. The capacitance is proportional to transducer area and inversely proportional to thickness, and thus increases with transducer size and frequency. The effective

capacitance can become quite large, placing severe demands for current on the pulser. Should the pulser be unable to supply sufficient instantaneous power to drive the cable and transducer capacitance, rise time and amplitude of the exciting pulse at the transducer suffer, limiting the sensitivity of the system at its source. The pulser becomes, effectively, a high equivalent source impedance.

Most conventional ultrasonic pulser circuits use a variation of an avalanche semiconductor to generate short, sharp spikes for the main bang. It is a common observation that pulse voltages measured across the terminals of the transducer are only fractions of the open-circuit pulser voltage, indicating insufficient instantaneous power capabilities; cable and transducer load the circuit severely. It is also a common observation that large and/or high-frequency transducers are less sensitive than would be expected in comparison with their smaller or lower frequency counterparts. This is a further indication of insufficient power from the pulser. In each of these cases, capacitive loading of the avalanche semiconductor through a relatively high source impedance increases the rise time and limits the final pulse voltage across the transducer.

The drive element in the present circuit is a fast, high-power field effect transistor (FET) [3] which is capable of supplying more than 50 A at a maximum of 200 V. It is connected as a saturated switch, see Figure 1. The switch is driven by a square pulse of adjustable width formed by a monostable multivibrator, which in turn is triggered by the leading edge of a TTL pulse supplied externally. The pulser output is terminated in $50\ \Omega$ to match RG-58 cable. The transducer end of the connecting cable is left unterminated.

The effectiveness of the circuit was tested as described below. It is illustrated by the following tests. These tests used moderately damped 19-mm diameter transducers of 2.25 and 10 MHz center frequency rigidly mounted to view a flat aluminum plate target in a water bath. Cable length was ~ 2 m. When using any of a series of standard commercial pulsers, all having avalanche semiconductors as the pulse-generating elements, the 2.25 MHz transducer produced pulse/echo signals which were typically 23 dB greater than those from the 10 MHz transducer. With the

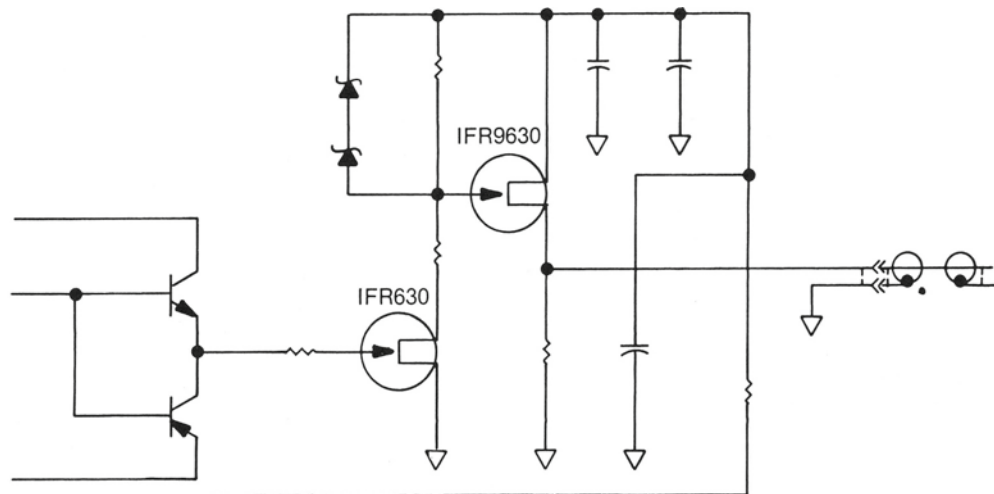


Fig. 1. Drive circuit for the pulser. Input to this circuit is a square wave formed by a monostable multivibrator.

substitution only of the present pulser, the signal from the 2.25 MHz transducer increased 6 dB, while that from the 10 MHz transducer increased 28 dB. Peak current requirements were 50 A for the 10 MHz transducer and about 10 A for the 2.25 MHz transducer; the ratio of current requirements was almost exactly what one would expect the capacitance ratios to be.

Rise time at the transducer terminals in a typical application is 7 ns, and fall time is 14 ns. This implies that the circuit is most useful for transducers below about 40 MHz in frequency. The maximum pulse repetition rate is limited by the high-voltage power supply in the present implementation to about 1.2 kHz.

Layout is critical to maintaining pulser bandwidth. The driving circuit and its supply components are mounted on solid copper, both for heat-sink and to provide adequate current paths. It is also important that any cabling connecting the driving circuit to the instrument panel be of high-quality; even short lengths of lower quality line can cause severe bandwidth limitations.

PREAMPLIFIER AND AMPLIFIER

The primary objectives of this design were low noise, stability, and low distortion combined with quick overload recovery. The design departs from conventional ultrasonic practice in several ways in order to achieve these in a manner applicable to a large automated system.

A building-block approach using separate, individually optimized modules for each function is used to provide complete software control economically for many-channeled systems. The complete chain of signal-conditioning modules includes: a preamplifier, amplifier, multiplex, gain control, filtering, and analog-to-digital converter (ADC). Separation of functions minimizes or eliminates deleterious interactions between functions.

The pulser and this entire chain are DC-coupled throughout to minimize baseline distortion and speed overload recovery. Interconnections are all matched to 50 Ω transmission characteristics.

Two types of amplifier modules are provided. The first includes a main-bang block and has a gain of 12 dB. This is the input stage and may be used alone or in combination with other stages as a remote preamplifier to reduce the effects of noise pickup in long transmission lines. The second type of module has a gain of 18 dB and does not include the block. These can be indefinitely "stacked" with patch cables, to obtain the desired overall gain. The designs of both types are optimized for stability and noise. Nominal bandwidth is 60 MHz, a good match for the pulser characteristics.

The main-bang block at the input to the first amplifier module type is an example of noise reduction techniques that have been employed. Circuit noise at this location is the most troublesome, since it receives the full amplification of the signal-conditioning chain along with the signal itself. The block is a linear gate derived from design practice for gamma-ray spectroscopy. The gate, shown in Figure 2, closes whenever the input signal rises above a fixed threshold that corresponds to the initial rise of the main bang. When the gate is open, that is, during useful amplification, the semiconductors are in their fully active state, minimizing noise generation. In contrast, the conventional main-bang block, a starved-current diode-bridge, induces significant additional shot noise.

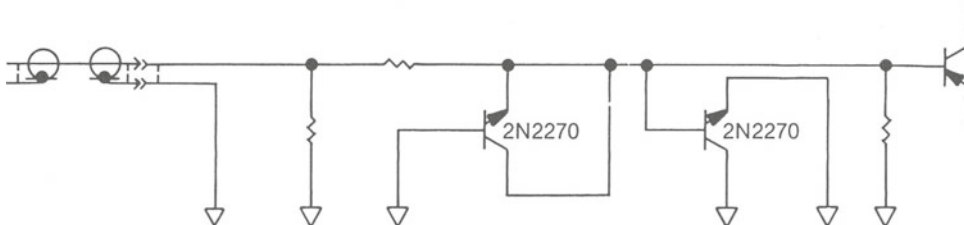


Fig. 2. Main-Bang block for receiver. Circuit is a linear gate which closes when input exceeds a set level, as during the main bang.

Gain control for the amplifier chain is provided by a coaxial attenuator [4] under computer control. This unit provides up to 64 dB of frequency-independent attenuation in half-dB steps. Since it is a separate, patchable module, it can be placed at any required location in the chain; in large automated systems, it is normally located just before the ADC so that one attenuator serves as gain control for all transducer channels.

Filtering, when used, is provided in separate modules containing banks of the desired filters. These, too, are patchable and can be placed wherever they are needed in the chain.

IMPLEMENTATION AND SYSTEM USE

Layout of pulsers and preamplifier/amplifiers is on standard cards which are dimensioned so that three modules of each type can fit side by side in one double-width Nuclear Instrument Module (NIM) unit. All input and output connectors are duplicated on front and rear panels. Each pulser card includes a 200 V DC-to-DC-conversion power supply [5].

Multichannel operation is accommodated through a separate two-level random multiplex (MUX) unit, which uses reed relays for signal transfer. The first level distributes a TTL main-bang trigger to the pulser for the channel being activated. This trigger pulse also initiates the ADC timing cycle. The second MUX level selects the receiver signal to be fed to the attenuator and ADC. Full closure of the MUX requires slightly less than 2 ms. Although fully electronic MUX circuits would be considerably faster, they would also introduce additional noise. The TTL main-bang trigger is derived from software, which permits both hardware and software to be fully synchronized. This low-level trigger is compatible with MUX properties, which would not be the case if the output of a single pulser were distributed to all transducers; further, the full power bandwidth of the pulser signal is preserved.

It is important to note that the pulser signal requires much larger bandwidth than does the transducer signal, if the optimum excitation conditions noted above are to be preserved. It is necessary, therefore, that high quality cabling be used throughout the system. The present design uses 50 Ω RG-58 cables. It was found that the more conventional RG-174, RG-178, and similar cables seriously degrade main-bang rise time, even in relatively short lengths; the degradation is ascribed to dispersion in these smaller-diameter cables.

No electronic "area of interest" gates are used in this system. The ADC [6] provides this function instead. The complete signal is captured by the ADC, and the required portions of it can usually be predetermined

and read out without wasting time on uninteresting portions of the signal; the ADC, in effect, consists of thousands of individually synchronized "gates" which can be selected after the fact.

PERFORMANCE AND SUMMARY

The sensitivity of such a system is significantly greater than that of conventional systems design. The increase comes from the pulser properties, the most important of which is the recognition of the need to minimize the effective source impedance of the driving circuit. The degree of improvement is a function of the capacitance of the transducer, and thus of its size and frequency; a 28-dB improvement in sensitivity was obtained for a large, relatively high frequency transducer in one system.

Typical noise obtained from the entire system connected for pulse/echo operation, including pulser, amplifier, and attenuator, is 50 μ V RMS referred to the input, measured at a 10 MHz bandwidth. The principal source of noise is the leakage current of the driver FET. (The noise can be reduced further in this circuit configuration only when better semiconductors become available; a configuration in which an active FET charges the transducer continuously except during transducer excitation would reduce this noise source considerably, at the cost of potential personnel safety problems.)

The 50 μ V noise performance of the system compares very favorably with that of conventional circuitry, and in fact can be 10 to 15 dB less, depending on a number of system details. The result is that, in at least one system, an improvement approaching 40 dB in SNR, and thus in effective dynamic range, has been obtained.

Stability and distortion have not been quantified. However, qualitative improvements, to the point where these parameters are no longer of concern, have been identified.

The pulser and preamplifier/amplifier modules were first used in a 12-channel system designed for precise "sonar" measurements of the cavity in the Three Mile Island-2 reactor. They are now being designed into a system for remote inservice inspection of the in-pile tubes of the Advanced Test Reactor at the Idaho National Engineering Laboratory. The modules continue to be used in laboratory investigations, where their SNR, stability, and low distortion are of particular usefulness in experiments requiring extensive signal processing.

ACKNOWLEDGMENT

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3. International Rectifier Part Number IRF-9630.
4. Matrix Part Number 6153-50-BNC.
5. Venus Scientific, Part Number CT2.
6. Lecroy Model TR8837E, in CAMAC format, is used typically in these systems. These provide large scratch-pad memories with pre- and posttrigger sampling of any desired area of interest.